QUARKONIUM DISSOCIATION IN A POLYAKOV–NAMBU–JONA-LASINIO QUARK PLASMA*

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We investigate the Mott effect for heavy quarkonia due to Debye screening of the heavy quark potential in a plasma of massless quarks and antiquarks. The influence of residual color correlation is investigated by coupling the light quark sector to a temporal gauge field driven by the Polyakov loop potential. This leads to an increase of the Mott dissociation temperatures for quarkonia states which stabilizes in particular the excited states, but has marginal effect on the ground states. The temperature dependence of binding energies suggests that the dissciation of the charmonium (bottomonium) ground state by thermal activation sets in at temperatures of 200 MeV (250 MeV).

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1. Introduction

Since the suggestion of J/ψ suppression as a signal of quark–gluon plasma (QGP) formation by Matsui and Satz [1] in 1986 the problem of quarkonium dissociation in hot and dense strongly interacting matter has played a key role for QGP diagnostics in relativistic heavy-ion collision experiments. The original idea was that in a QGP the string tension of the confining potential vanishes and the residual one-gluon exchange interaction undergoes a Debye

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screening by the color charges of the plasma. When the temperature dependent Debye radius $r_{\mathrm{D}}(T)$ (the inverse of the Debye mass $m_{\mathrm{D}}(T)$) becomes shorter than the Bohr radius of the charmonium ground state (J/ψ) then the Mott effect [2] (bound state dissociation) occurs and the corresponding temperature is $T_{\mathrm{Mott}}^{J/\psi}$. This simple idea grew up to a multifacetted research direction when not only in the first light ion–nucleus collisions at the CERN NA38 experiment, but also in proton–nucleus collisions at Fermilab J/ψ suppression has been found so that there is not only a QGP but also a cold nuclear matter effect on charmonium production, see [3] for a recent review.

If one wants to explore the question of screening in a plasma more in detail then a variety of approaches is available in the literature, from the original Debye–Hückel approach [4] applicable to any vacuum potential (for example the Cornell potential), over the thermodynamic Green functions approach to the *ab initio* studies of heavy-quark potentials in lattice QCD. With the obtained medium-dependent potentials one can then study the bound state problem by solving the thermodynamic T-matrix for quarkonia [5], or the equivalent Schrödinger-type wave equation where medium effects are absorbed in a plasma Hamiltonian [3,6].

On the other hand one may calculate proper correlators directly from lattice QCD and extract from them spectral functions [7]. There is an intriguing disagreement between the Mott temperatures deduced from these spectral functions and those of the potential models: From the lattice data for quarkonium correlators one has extracted $T_{J/\psi}^{\mathrm{Mott}} \approx 1.9\,T_{\mathrm{c}}$ while in potential model calculations $T_{J/\psi}^{\mathrm{Mott}} \approx 1.2\,T_{\mathrm{c}}$. This problem has lead to the discussion of the proper thermodynamical function to be used as a potential in the Schrödinger equation, see [3,8] and references therein.

In this contribution we follow the recently suggested [9] modification of the standard one-loop calculation of the Debye mass in thermal Quantum Field Theory [10,11] in the framework of the Polyakov–Nambu–Jona-Lasinio model, now widely used for a microscopic QCD-motivated description of mesons in quark matter [12, 13]. We then solve the Schrödinger equation for charmonium and bottomonium states with the plasma Hamiltonian [3] corresponding to the screened Cornell potential [14] and obtain the Mott dissociation temperatures of these states.

2. Debye-screening in a PNJL quark plasma

Given the static interaction potential $V(q)$, $q^2 = |\boldsymbol{q}|^2$, the statically screened potential is given by a resummation of one-particle irreducible diagrams ("bubble" resummation = RPA)

$$V_{\mathrm{sc}}(q) = V(q)/[1 + F(0;\boldsymbol{q})/q^2]\,, \tag{1}$$

where the longitudinal polarization function $F(0; \boldsymbol{q}) = -\Pi_{00}(0; \boldsymbol{q})$ in the finite T case can be calculated within thermal field theory as

$$\Pi_{00}(i\omega_l; \boldsymbol{q}) = g^2 T \sum_{n=-\infty}^{\infty} \int \frac{d^3p}{(2\pi)^3} \operatorname{Tr} \left[\gamma^0 S_\Phi(i\omega_n; \boldsymbol{p}) \gamma^0 S_\Phi(i\omega_n - i\omega_l; \boldsymbol{p} - \boldsymbol{q}) \right] . \tag{2}$$

Here $\omega_l = 2\pi l T$ are the bosonic and $\omega_n = (2n + 1)\pi T$ are the fermionic Matsubara frequencies of the imaginary-time formalism. The symbol Tr stands for traces in color, flavor and Dirac spaces. S_Φ is the propagator of a massless fermion coupled to the homogeneous static gluon background field φ_3. Its inverse is given by [12, 13]

$$S_\Phi^{-1}(\boldsymbol{p}; \omega_n) = \boldsymbol{\gamma} \cdot p + \gamma_0 i\omega_n - \lambda_3 \gamma_0 \varphi_3 , \tag{3}$$

where φ_3 is related to the Polyakov loop variable defined by [12]

$$\Phi(T) = \tfrac{1}{3} \operatorname{Tr_c}(e^{i\beta\lambda_3\varphi_3}) = \tfrac{1}{3} (1 + 2\cos(\beta\varphi_3)) .$$

The physics of $\Phi(T)$ is governed by the temperature-dependent Polyakov loop potential $\mathcal{U}(\Phi)$, which is fitted to describe the lattice data for the pressure of the pure glue system [12]. After performing the color-, flavor- and Dirac traces and making the fermionic Matsubara summation, we obtain in the static, long wavelength limit

$$\Pi_{00}(\boldsymbol{q}) = \frac{2N_c N_f g^2}{\pi^2} \int_0^\infty dp\, p^2 \frac{\partial f_\Phi}{\partial p} = -2g^2 T^2 I(\Phi) = -m_D^2(T) , \tag{4}$$

where $m_{\mathrm{D}}(T)$ is the Debye mass, the number of degrees of freedom is $N_c = 3$, $N_f = 2$ and $f_\Phi(p)$ is the quark distribution function [13]. For the discussion of imaginary parts of the polarization function and their relation to kinetics see, *e.g.*, [11]. In comparison to the free fermion case [10, 11] the coupling to the Polyakov loop variable $\Phi(T)$ gives rise to a modification of the Debye mass, given by the integral

$$I(\Phi) = \frac{12}{\pi^2} \int_0^\infty dx\, x \frac{\Phi(1 + 2e^{-x})e^{-x} + e^{-3x}}{1 + 3\Phi(1 + e^{-x})e^{-x} + e^{-3x}} . \tag{5}$$

The temperature dependence of $\Phi(T)$ is taken from Ref. [15]. In the limit of deconfinement ($\Phi = 1$), the case of a massless quark gas is obtained ($I(1) = 1$), while for confinement ($\Phi = 0$) one finds that $I(0) = 1/9$. Taking as the unscreened vacuum potential the one-gluon exchange form $V(q) = -4\pi\alpha/q^2$, $\alpha = g^2/(3\pi)$, the Fourier transform of the Debye potential results as statically screened potential, $V_{\mathrm{sc}}(q) = -4\pi\alpha/[q^2 + m_{\mathrm{D}}^2(T)]$.

3. Schrödinger equation and Mott temperatures

In order to calculate the temperature dependence of the two-particle energies $E_{nl}(T)$ for charmonium and bottomonium states in a PNJL quark plasma, we solve the Schrödinger equation

$$H^{\mathrm{pl}}(r;T)\phi_{nl}(r;T) = E_{nl}(T)\phi_{nl}(r;T)\,, \tag{6}$$

for the Hamiltonian [3]

$$H^{\mathrm{pl}}(r;T) = 2m_Q - \alpha\,m_{\mathrm{D}}(T) - \frac{\nabla^2}{m_Q} + V(r;T)\,, \tag{7}$$

with the screened Cornell potential [3, 14]

$$V(r;T) = -\frac{\alpha}{r}\,e^{-m_{\mathrm{D}}(T)r} + \frac{\sigma}{m_{\mathrm{D}}(T)}\left[1 - e^{-m_{\mathrm{D}}(T)r}\right]\,, \tag{8}$$

where parameters are fitted to the vacuum spectroscopy of heavy quarkonia by $\alpha_s = 0.471 = 3\alpha/4$, $\sigma = 0.192\ \mathrm{GeV}^2$ and the heavy-quark masses $m_c = 1.94\ \mathrm{GeV}$, $m_b = 5.1\ \mathrm{GeV}$. Here we use the Debye mass of the previous section with the temperature dependence of $\Phi(T)$ taken from a nonlocal PNJL model [15]. Note that the Hamiltonian (7) contains a temperature-dependent shift of the continuum edge due to the Hartree selfenergies of the heavy quarks in the potential (8), which results in a definition of the dissociation energies as

$$E_{nl}^{\mathrm{diss}}(T) := 2m_Q + \frac{\sigma}{m_{\mathrm{D}}} - \alpha\,m_{\mathrm{D}} - E_{nl}(T)\,, \tag{9}$$

and of the Mott temperatures as $E_{nl}^{\mathrm{diss}}(T_{nl}^{\mathrm{Mott}}) = 0$.

In the upper panels of Fig. 1 we show the temperature dependence of the two-particle energies (masses) of the lowest heavy quarkonia states at rest in the medium together with the corresponding two-particle continuum edge for charmonia (left) and bottomonia (right). The coupling to the Polyakov loop potential leads to a suppression of the quark–antiquark excitations responsible for the screening of the heavy-quark potential in the present model. This entails a stabilization of the bound states (solid lines) relative to the case without that coupling (dashed lines). In the lower panels we show the corresponding binding energies $E_{\mathrm{B}} = -E_{nl}^{\mathrm{diss}}$. Comparison with the available thermal energy of medium particles ($E_{\mathrm{th}} = T$) shows that Mott dissociation by thermal activation [16] is possible well below the Mott temperatures estimated from the solution of the Schrödinger equation. For more detailed discussions of the dissociation kinetics of heavy quarkonia, see the recent review [3] and references therein.
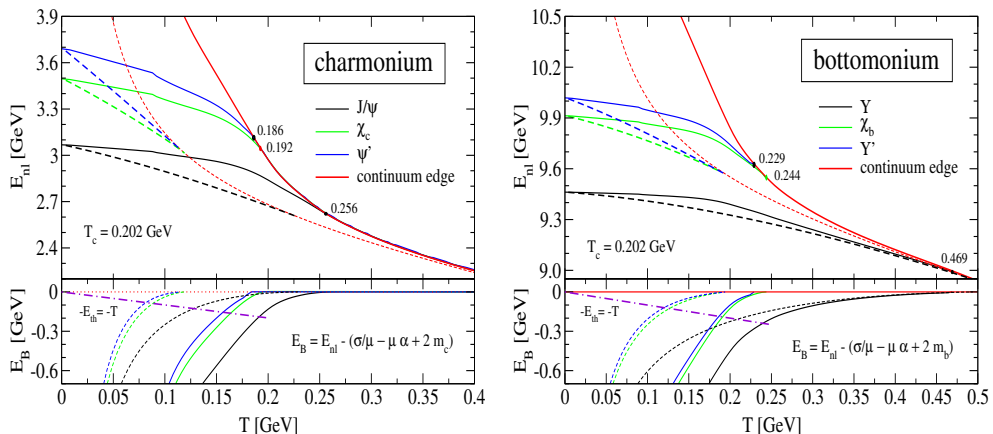
Fig. 1. Upper panels: Temperature dependence of the two-particle energies (masses) of the lowest heavy quarkonia states at rest in the medium together with the corresponding two-particle continuum edge for charmonia (left) and bottomonia (right) with (solid lines) and without (dashed lines) coupling to the Polyakov-loop potential. Lower panels: Temperature dependence of the binding energies $E_B = -E_{nl}^{\mathrm{diss}}$, compared to the available thermal energy of medium particles $E_{\mathrm{th}} = T$. For discussion, see text.

4. Conclusions

We have applied the methods of thermal field theory to estimate the effects of Debye screening on heavy quarkonia bound state formation. In order to account for residual effects of confining color correlations in the deconfined phase, we have used the PNJL model in the evaluation of the one-loop polarization function. As expected, a stabilization of bound states in the vicinity of the critical temperature for $T > T_c$ is obtained. We have solved numerically the Schrödinger equation to derive the Mott criterion for bound states of the statically screened Cornell potential and obtained Mott temperatures in good agreement with previous results from nonrelativistic potential models exploiting lattice QCD singlet free energies as potentials in the Schrödinger equation for heavy quarkonia. This agreement with previous results (see, *e.g.*, Ref. [8]) includes also higher quarkonia resonances. For these states the stabilization effect is most pronounced since their Mott temperatures lie in the region of temperatures where the suppression of quark–antiquark excitations due to the Polyakov-loop potential is the largest. Due to the lowering of the dissociation energies for heavy quarkonia states, their dissociation become possible by thermal activation already well before the Mott temperatures are reached. According to the present work, even the tightly bound bottomonium ground state Υ may get "boiled away"

at temperatures $T \sim 250\,\mathrm{MeV}$, well accessible already at RHIC. The detailed discussion of the heavy quarkonia dissociation kinetics and its relationship to imaginary parts of the heavy-quark potentials [11] is beyond the scope of the present contribution.

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